(NASA-CR-142231) OBSERVATIONS OF PLASMAS IN THE JOVIAN MAGNETOSPHERE (Iowa Univ.) 43 p HC $3.75 CSCL 03B

N75-19097

Unclas

G3/90 12382

Research was sponsored in part by the Office of Naval Research under contract N00014-68-A-0196-0009.

Department of Physics and Astronomy
THE UNIVERSITY OF IOWA
Iowa City, Iowa 52242

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER U. of Iowa 75-5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) OBSERVATIONS OF PLASMAS IN THE JOVIAN MAGNETOSPHERE		5. TYPE OF REPORT & PERIOD COVERED Res. Report
		6. PERFORMING ORG. REPORT NUMBER N00014-68-A-0196-0009
7. AUTHOR(s) L. A. Frank, K. L. Ackerson, J. H. Wolfe and J. D. Mihalov		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Physics and Astronomy The University of Iowa Iowa City, Iowa 52242		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, Virginia 22217		12. REPORT DATE January 1975
		13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Jovian magnetosphere, Jovian plasmas, Jovian decametric radiation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

[See page following]

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

U. of Iowa 75-5

OBSERVATIONS OF PLASMAS IN THE JOVIAN MAGNETOSPHERE*

by

L. A. Frank, K. L. Ackerson, J. H. Wolfe+
and J. D. Mihalov+

January 1975

Department of Physics and Astronomy
The University of Iowa
Iowa City, Iowa 52242

*Research supported in part by the National Aeronautics and Space Administration under grant NGL-16-001-002 and by the Office of Naval Research under contract N00014-68-A-0196-0009.

+At Space Physics Branch, NASA Ames Research Center, Moffett Field, California 94035.

Abstract

Large intensities of low-energy protons were observed deep within the Jovian magnetosphere with the plasma instrumentation on Pioneer 10 during the encounter of this space probe with Jupiter. The energy range of the electrostatic analyzer was 108 eV to 4.80 keV during encounter. Inside the flux tubes of the Galilean moon Io is a 'plasmasphere' of protons with relatively high densities, 100 $(cm)^{-3}$, extending toward the planet to at least 2.8 R_J. The characteristic thermal energies of these protons are about 100 eV. The flux tubes of Io are positioned on a severe decrease of these densities with increasing Jovicentric radial distances--a plasmapause. The relationship of Io to this plasmapause is quite likely to be fundamental to the Io-modulation of decametric radio emissions. The proton densities in the vicinity of Io are also sufficiently high to limit the azimuthal extent of the partial torus of hydrogen gas from Io by the mechanism of charge exchange. At greater distances, beyond the plasmapause, is found a great torus of plasma encircling Jupiter with densities in the range 10 to 15 $(cm)^{-3}$ and thermal energies about 400 eV. The moon Europa is embedded in this torus, or 'ring current'. This ring current is extended into a thin plasma disc at greater radial distances. At 15 R_J the thickness of this disc is only 2 R_J and proton densities are about 1 $(cm)^{-3}$. The source of these low-energy protons is believed to be the Jovian ionosphere. The mechanisms for the formation of the Jovian plasmasphere, ring current and plasma disc must differ substantially from those dominantly participating in the terrestrial magnetosphere.

I. Introduction

The interplanetary probe Pioneer 10 has opened a new frontier for studies of planetary magnetospheres with its exciting flyby of the planet Jupiter. In contrast to the earth's magnetosphere, with the exception of its plasmasphere, the Jovian magnetosphere is dominated by the great corotational velocities associated with Jupiter's large size and short rotational period [Smith _et al_., 1974; Van Allen _et al_., 1974; Simpson _et al_., 1974; Fillius and McIlwain, 1974; Trainor _et al_., 1974]. Our present picture of the Jovian magnetosphere is one of an enormous 'magnetodisc' of energetic charged particles, with a diameter of about 200 Jovian radii in the equatorial plane and within which is embedded a thin disc of plasma. This model of the Jovian magnetosphere is based upon the aforementioned comprehensive observations of magnetic fields and energetic charged particle intensities during the encounter. No direct measurements of the plasmas deep within the Jovian magnetosphere have yet been reported. It is our purpose herein to present such plasma observations -- specifically, of low-energy ion distributions. The plasma instrumentation aboard Pioneer 10 was designed for detailed measurements of the solar wind and of planetary magnetosheaths. As with all plasma instruments with these goals as primary objectives, the Pioneer-10 plasma analyzers lack the sensitivity and energy range required for comprehensive surveys of the hot, quasi-isotropic plasmas found within planetary magnetospheres. Specially designed electrostatic analyzers have been employed within the earth's magnetosphere to surmount this obstacle [cf. Frank, 1967]. Such analyzers were not included with the Pioneer-10 detector complement. However, because of the great importance of plasma measurements to any final assessment of the dynamics of the Jovian magnetosphere, a vigorous analysis of the plasma instrument responses was undertaken. The results of this analysis provide direct information of several remarkable plasma domains in the Jovian magnetosphere and tantalizing hints of a cornucopia of further fascinating plasma phenomena.

II. Observations

The *in situ* observations of low-energy proton intensities in the Jovian magnetosphere reported here were gained with one of the Ames Research Center electrostatic analyzers on Pioneer 10, the medium-resolution analyzer with collectors and electrometers employed as plasma sensors [cf. Wolfe *et al*., 1974]. This analyzer comprises quadrispherical plates with a mean radius from their common centers of curvature of 12 cm and a separation of 1 cm. The corresponding values for the analyzer constant and energy resolution are 6.0 and 0.16, respectively. During the encounter of the spacecraft with Jupiter the plasma analyzer was operated in a mode which covered the energy range 100 eV to 4.8 keV for positive-ion intensities within 24 energy passbands. This electrostatic analyzer determines only the energy-per-unit charge of the positive ions. Our assumption that the positive ions can be identified as dominantly protons is based upon the facts that protons are the major constituents of both the solar wind and Jovian ionosphere and that these two plasma domains are the only apparent viable sources for the ion intensities found in the Jovian magnetosphere. This situation differs from that encountered within the terrestrial magnetosphere where heavy ions, such as of oxygen, are drawn from the ionosphere into the magnetospheric plasmas [Shelley *et al*., 1972; Chappell, 1972].

The viewing geometry for the electrostatic analyzer during encounter is summarized in Figure 1. At the exit aperture of the quadrispherical plates are positioned five current-collecting plates, each with a sensitive electrometer for current measurement. Hence the total viewing solid angle, 140° x 4°, is divided into five contiguous fan-shaped fields-of-view. The dimensions of the three inner fields-of-view are 15° x 4° and those of the outer two are 47.5° x 4°. The projections of these fans of acceptance onto the ecliptic plane are shown for two positions along the trajectory in Figure 1. The field-of-view for the middle detector is centered along the spacecraft spin axis, and thus is directed toward earth during the encounter. We will employ the responses of this sensor in the present analyses. The instrument electronics are programmed to continuously sample the outputs of the electrometer within a given energy passband as the spacecraft rolls about its spin axis and to telemeter the maximum response and the corresponding roll, or clock, angle for a spacecraft rotation of 180°. In the hot, quasi-isotropic plasmas of the Jovian magnetosphere, the sampling of ion intensities occurs at more-or-less random roll angles for the electrostatic analyzer unless a substantial anisotropy is detected. This situation gives rise to one difficulty in analyses of the measurements--the energetic charged-particle intensities stimulating the background responses of the electrometers vary with roll phase due to a combination of anisotropy of these intensities and of the uneven shielding of the electrometers.

The fan-shaped field-of-view of the electrostatic analyzer samples the corotational velocity vectors along the inbound trajectory segment from about the orbit of Europa through periapsis (see Figure 1). The proton energies corresponding to corotational velocities at periapsis and Europa are about 6 eV and 75 eV, respectively, and are less than the lower bound of the energy range of the analyzer. For proton intensities within the energy range of the analyzer, corotational effects should be readily observable in the vicinity of Europa, but not at periapsis.

The following displays of observations, and of the trajectory of Figure 1, are all labelled with earth-received time (E.R.T.). Earth-received time is the Universal Time at which the telemetry signal from the spacecraft was received at earth. To compute the Universal Time for the measurement at the spacecraft it is necessary to subtract a signal propagation delay of about 46 minutes from E.R.T.

The three factors which were the major obstacles in analyses of the telemetered responses of the analyzer were the substantial background currents due to penetrating energetic charged particles, the roll modulation of these background responses associated with the aforementioned uneven shielding of the instrument electronics, and the response levels which were near the electrometer thresholds. These problems were overcome to a great extent by applying background current corrections, by limiting first analyses to the center electrometer, and by employing the familiar technique of color-coded energy-time spectrograms of instrument responses. Examples of these spectrograms of analyzer responses are given in Figure 2. Approximately 12,000 samples of the responses of the center electrometer for 4 December 1973 have been encoded into the upper energy-time (E-t) spectrogram. However, due to the nature of the measurements gained with this analyzer the responses are encoded in a different manner than those commonly found in the literature for plasmas within the earth's magnetosphere [cf. Frank and Ackerson, 1971]. First a background response was defined for each scan of the proton energy spectrum as the minimum electrometer response observed in the 24-sample energy scan. This background response was then subtracted from each of the 24 measurements and the differences are plotted according to the color scale at the right-hand side of Figure 2 (large response relative to background is red and low responses are blue). Since the response of the electrometer is logarithmically proportional to the current collected by the plate at the exit aperture of the analyzer, the spectrograms can be usefully employed to identify the presence and general character of low-energy proton intensities but not for comparison of absolute intensities among the energy scans. A similar treatment of the responses of the two electrometers corresponding to the two fields-of-view adjacent to the central viewing fan is shown as a corroborating observation in the lower E-t spectrogram of Figure 2. Two different plasma regimes are readily evident in these spectrograms -- an intense low energy proton distribution observed before and after periapsis (0315 E.R.T.) and a higher energy proton regime centered at about 1200 E.R.T. Reference to Figure 1 is useful in assessing the location of the plasmas relative to the trajectory and Jupiter. The solid, remarkable signatures of large low-energy proton intensities revealed in these spectrograms provided much of the impetus to further carefully examine their energy spectrums and spatial distributions.

Large intensities of electrons with energies greater than several MeV are the dominant contributors to background currents for the electrometers of the electrostatic analyzer. Omnidirectional intensities of electrons with $E > 9$ MeV [Fillius and McIllwain, 1974] and the equivalent background intensities for the electrostatic analyzer are compared in Figure 3 for observations during 4 December (the upper spectrogram of Figure 2). The background responses are calculated by employing the minimum electrometer current for a given spectral scan as the background current for all energy steps and subsequently converting these currents into an equivalent background intensity with the known unidirectional geometry factors for the instrument. This equivalent background intensity is convenient for the direct comparison with energetic electron intensities and measurements of the directional proton intensities shown in Figure 3. The background intensities (solid circles) for the analyzer are approximately proportional to penetrating electron intensities (upper panel) as expected. A comparison with electron intensities with $E > 3$ MeV [Simpson et al., 1974] provides a similar result. The equivalent background intensities fall to threshold values, i.e., no background responses, by 1130 E.R.T. at energetic electron ($E > 9$ MeV) intensities of about 10^6 electrons $(cm^2\text{-sec})^{-1}$. The directional intensities of protons within the energy range extending from 108 eV to 4.80 keV are shown in the lower panel (open circles) of Figure 3. It is noteworthy that these intensities are not proportional to the background responses of the instrument and are in fact the signature of large, low-energy proton intensities within the Jovian magnetosphere. Over the period 0000 E.R.T. to occultation at about 0430 E.R.T. (periapsis is at 0315 E.R.T.) these intensities are relatively constant at approximately 10^8 $(cm^2\text{-sec-sr})^{-1}$, or an omnidirectional intensity of greater than 10^9 $(cm^2\text{-sec})^{-1}$ which is comparable to or greater than that of the solar wind at Jupiter. Substantial, though lesser, intensities of protons are observed along the outbound trajectory until 1320 E.R.T. when the intensities declined to values below the instrument threshold of 6×10^6 $(cm^2\text{-sec-sr})^{-1}$.

Proton densities have been calculated from our measurements of directional intensities by assuming isotropy for the angular distributions. These densities are presented as a function of E.R.T. in Figure 4. The magnetic shell parameters L (courtesy of C.E. McIlwain) and pitch angles α at the spacecraft position (via magnetometer measurements, courtesy of E. J. Smith) are given along the top border of the figure. The magnetic flux tubes encountered by the moons Amalthea, Io and Europa are shown by the shaded bands which are sufficiently broad to span the values obtained with divers magnetic field models [cf. Smith et al., 1974; Van Allen et al., 1974]. Estimates of the overall inaccuracy in the determination of these densities are also given for two representative measurements in this, and subsequent figures. These estimates include those attributable to background corrections, electrometer instability near its threshold currents and calculations of geometry factors for quasi-isotropic proton intensities. There are four remarkable plasma features evident in the density profile of Figure 4: (1) high densities of protons, 30 to 60 $(cm)^{-3}$ inside the orbit of Io; (2) a steep decline, or gradient, of proton densities at the orbit of Io; (3) a sparse, sporadic population at 0745 to 0930 E.R.T. and (4) a fluctuating proton zone with typical densities 10 $(cm)^{-3}$ in which is embedded the Europa flux tubes.

The observations of a rapid decrease of proton densities with increasing Jovicentric radial distance in the vicinity of the Io flux tubes during the outbound segment of the encounter trajectory as noted above are similar to such measurements for the inbound traversal of the Io flux tubes. These inbound observations on 3 December are summarized in Figure 5. The corresponding Jovicentric radial distances are given at the top of this figure. An enhancement of ion densities is centered at 2250 E.R.T. A similar, but lesser increase of densities at the Io flux tubes, which was superposed upon a severe overall decrease of densities with increasing distance, was also recognizable in the outbound measurements (see Figure 4). The decrease of proton densities in the vicinity of the Io flux tubes is roughly by factors of about 4 per Jovian radius for both the inbound and outbound observations.

The energy spectrums for protons found inside the orbit of Io and those in the regions beyond Io substantially differ. A brief inspection of the spectrograms of Figure 2 for the periods 0000 to 0730 E.R.T. and 0930 to 1300 E.R.T. yields clear evidences of these differences in proton energy spectrums for these two regimes. A typical directional, differential spectrum for proton intensities at positions inside those of the Io flux tubes is given in Figure 6. This proton spectrum is approximated well by a Maxwellian distribution with number density $N = 60\ (cm)^{-3}$ and with $kT = 95$ eV. Note that a major fraction of the protons, $40\ (cm)^{-3}$, for the fitted distribution is within the energy range of the electrostatic analyzer. The corresponding corotational energy for a proton at this position along the trajectory is about 9 eV, well below the instrument energy range. This region has been labelled as 'the plasmasphere' due to the similarity of its spatial configuration and location with those of the familiar plasmasphere in the terrestrial magnetosphere -- relatively constant densities of low energy ions with increasing radial distance on the inner L-shells with a rapid decrease in densities at the outer boundary, or plasmapause. This spatial similitude does not imply here that the mechanisms for formation of the boundaries are thought to be similar. This matter is further investigated in the following Discussion section. A further example of the proton spectrums gained in this Jovian plasmasphere is shown in Figure 7. This spectrum is for a period only a few minutes before periapsis and is given here to provide an example of one of the poorer fits of a single-scan spectrum to a Maxwellian. The Maxwellian, N = 85 $(cm)^{-3}$ and kT = 105 eV, approximates the observations within the accuracy of the intensity determinations. However, a 'power-law' fit, $E^{-1.3}$, would also appear satisfactory. Near periapsis the greater background currents due to the extremely high intensities of penetrating particles increased the errors in determination of the relative differential intensities during a given spectral scan. This problem did not arise at other positions within the plasmasphere. The measured proton densities within the energy range 108 to 1100 eV at periapsis (R = 2.8 R_J) are approximately 50 $(cm)^{-3}$, and similar to those densities observed throughout the Jovian plasmasphere.

No signature of a pronounced decrease of proton densities in the plasmasphere near the periapsis of the Pioneer-10 trajectory at 2.8 R_J is evident in the observations. However, analyses of similar measurements with Pioneer 11 at Jovicentric radial distances to 1.6 R_J will clarify the geometry of this plasma regime near the planet.

The proton intensities in the vicinity of the orbit of Europa are characterized by markedly higher temperatures and lower densities relative to those of the plasmasphere as reported above. A typical proton spectrum gained along the outbound trajectory is shown in Figure 8 (cf. 1206 E.R.T., upper panel, Figure 2). The energy spectrum is satisfactorily approximated by a Maxwellian distribution with $N = 14\ (cm)^{-3}$ and $kT = 400$ eV. The computed corotational energy is 76 eV for a proton at this position along the trajectory, which is sufficiently near the lower limit of energy range of the electrostatic analyzer to observe corotational effects in the angular distributions. The results of such a study will be the subject of a subsequent report. The large proton densities encountered during the period of about 0930 to 1230 E.R.T. (see Figure 4) are the signature of a great torus of plasma or, more colloquially, a 'ring current' surrounding Jupiter at Jovicentric radial distances of approximately 8 to 12 R_J near the equatorial plane.

A summary of the geometry of these various plasma regimes in the magnetic meridional plane through the spacecraft position is offered in Figure 9. The magnetic field model employed here is a centered dipole tilted at 9.5° along System III (1957) longitude 230° [Van Allen et al., 1974]. The spacecraft trajectory provided an excellent opportunity for measurements of the plasmas near the magnetic equator out to about 10 R_J, especially during the outbound segment. The primary features of the various plasmas are given in the figure legends. The locations of the magnetic flux tubes encountered by Io and Europa are also shown in Figure 9. Io flux tubes are positioned near the boundary of the high-density, low-energy proton populations at lesser radial distances and Europa is embedded in the hotter proton distributions of the Jovian ring current. In the region between the flux tubes of Io and the ring current is found a region of lesser, and sporadically appearing, proton intensities. Analyses of their energy spectrums yield number densities 1 to 10 $(cm)^{-3}$ with kT = 400 (± 100) eV. However, these observations do not preclude the existence of a larger density of low-energy protons confined to low latitudes $\lambda_m = \pm 10°$ near the magnetic equatorial plane in this 'sporadic zone'. At Jovicentric radial distances at about 10 R_J the proton energy densities in the ring current and plasma sheet appear to be sufficiently great to effect a measurable distortion of the Jovimagnetic fields near the equator. At 10 R_J the energy densities, $\mathcal{E}$, are about 2×10^{-8} erg $(cm)^{-3}$ and the equatorial magnetic field is about 400 gammas [Smith et al., 1974]. The estimated perturbation field due to diamagnetism is $4\pi\mathcal{E}B^{-1} \simeq 6$ gammas. However, the perturbation fields from the external currents associated with the plasma disc can be expected to be larger by roughly an order of magnitude. The magnetic field lines at $R \geq 10\ R_J$ have been distorted to reflect the increasingly important deformations with greater Jovicentric radial distances, which are attributable to the presence of this plasma. All magnetic field lines traversed by the segment of spacecraft trajectory shown in Figure 9 are assumed to be closed (i.e., not open to interplanetary field lines) and are populated with substantial intensities of energetic charged particles [cf. Fillius and McIlwain, 1974; Van Allen *et al*., 1974; Simpson *et al*., 1974].

The most opportune period for direct observations of the plasma within the plasma sheet, or 'disc', in the outer Jovian magnetosphere was 1300 to 1400 E.R.T. on 3 December. Reference to Figure 9 shows that the corresponding Jovicentric radial distance of the spacecraft position is about 14 R_J. An example of the proton energy spectrums within the plasma sheet is shown in Figure 10. Temperatures for the protons are similar to those found within its Jupiterward extension into the ring current. However, proton densities are severely less, 0.5 to 1 $(cm)^{-3}$, in the plasma sheet and are typically less by factors of 10 than ring current densities. In fact proton intensities approach the sensible limit, or threshold, of the plasma analyzer. The corotational energy of a proton at this position within the plasma sheet is 160 eV, a substantial fraction of the characteristic thermal energy of the protons. A detailed study of the corotational effects on the proton angular distributions will be forthcoming soon. This traversal of the plasma sheet provides a direct determination of the thickness of the plasma sheet at about 15 R_J. The plasma sheet is remarkably thin with a dimension of only 2 R_J taken normal to the equatorial plane.

It is of interest to compare these observations of low-energy protons with other simultaneous measurements gained with Pioneer 10. Fillius and McIlwain [1974] have reported the omnidirectional intensities of electrons with E > 160 keV during the near-Jupiter encounter. These observations are compared with our determinations of proton densities in Figure 11. The small enhancement of electron (E > 160 keV) intensities at 0645 E.R.T. is positioned at or near the plasmapause. A similar effect is evident also for the inbound observations (cf. Figure 5, present work, and Fillius and McIlwain [1974]). The outbound traversal of the ring current and plasma sheet as determined from visual inspection of the spectrograms of Figure 2 is identified by vertical dashed lines in Figure 11. Rapid fluctuations of electron (E > 160 keV) intensities are detected coincident with the traversal of this high density plasma. These observations may be indicative of acceleration or turbulence in this outer plasma regime.

III. Discussion

Our present analysis of in situ measurements of the low-energy proton intensities deep within the Jovian magnetosphere with the plasma instrumentation on Pioneer 10 has established the existence of several remarkable plasma domains. Inside the flux tubes of Io at 6 R_J is a 'plasmasphere' of protons of relatively high densities, 100 $(cm)^{-3}$, extending toward the planet to at least 2.8 R_J. The characteristic thermal energies for these protons are $kT \sim 100$ eV. The flux tubes of Io are positioned on a severe decrease of proton densities with increasing Jovicentric radial distance. This plasma boundary is referred to as the plasmapause. Beyond Io a 'sporadic zone' of proton densities ranging from ≤ 1 to 10 $(cm)^{-3}$ is encountered. The radial dimensions of this zone are 1 to 2 Jovian radii at the equator. Adjacent to this sporadic region at about 8 R_J, again measured along the equator, is the inner boundary of a great torus of plasma with densities typically in the range 10 to 15 $(cm)^{-3}$ and thermal energies $kT \simeq 400$ eV. The Galilean moon Europa is embedded within this ring current. The ring current is extended outwards into the distant Jovian magnetosphere in the form of a thin plasma disc. At 15 R_J the thickness of this disc is only 2 R_J and proton densities are in the range of 0.5 to 1.0 $(cm)^{-3}$. A graphical summary of these results is shown in Figure 9.

Although the spatial configuration of the Jovian plasmasphere is similar to that of the terrestrial plasmasphere, the mechanisms responsible for their outer boundaries, or plasmapauses, are almost certainly dissimilar. At the terrestrial plasmapause the magnitudes of the corotational electric fields are approximately equal to those of electric fields induced by the flow of the solar wind past the magnetosphere [Brice, 1967]. These electric field strengths are in the range of microvolts $(cm)^{-1}$. The corotational electric fields at the Jovian plasmapause are greater by factors ~ 1000 at 6 R_J. Moreover, the 'cross-tail' electric fields in the Jovian magnetosphere due to the solar wind should be expected to be less than at the earth. Hence these electric fields probably play no important role in the formation of the Jovian plasmapause. Indeed corotational and cross-tail fields become comparable at 50 to 100 R_J in the Jovian magnetosphere [Brice and Ioannidis, 1970; cf. Eviatar and Ershkovich, 1974]. We suggest that this mechanism may be important in effecting the large fluctuations in magnetopause position observed with Pioneer 10. Thus far in our first analyses, the only feature or mechanism which we can clearly associate with the position of the Jovian plasmapause is the obvious presence of the moon Io. The high temperatures, $\sim 10^6$ °K, of the protons within the Jovian plasmasphere also appear to be not immediately accounted for. All of the plasma measurements reported here were gained in the centrifugally dominated region of the Jovian magnetosphere [Carr and Gulkis, 1969]. Pioneer 10 did not penetrate into the gravitationally dominated region. Perhaps a mechanism such as hydromagnetic disturbances associated with large-scale interchange motions as proposed by Piddington [1967] can yield these high temperatures.

The striking modulation of decametric radiations from Jupiter by its moon Io has provided ample stimulus for close examination of all _in situ_ measurements at the Io flux tubes with Pioneer 10 for evidences of charged-particle acceleration. For reviews of Jovian decametric radiation the reader is referred to Warwick [1967] and Carr and Gulkis [1969]. The substantial signatures of the 'sweeping', or absorption, of energetic charged-particle intensities by Io and its companion moons have been gained, but no direct evidences of particle acceleration associated with Io are readily evident in these measurements with the exception of small increases of electron intensities with $E > 160$ keV at the Io flux tubes [Fillius and McIlwain, 1974]. We have reported here that the Io flux tubes are positioned in a unique feature of the Jovian magnetosphere -- its plasmapause. The densities measured within these flux tubes ranged from 10 to 100 $(cm)^{-3}$. These values are below the upper limit for densities above the ionosphere of Io of about 500 $(cm)^{-3}$ as established by radio occultation observations with Pioneer 10 [Kliore _et al_., 1974]. The System III longitudes for the crossings of the Io flux tubes by Pioneer 10 were approximately 180° and 300° for the inbound and outbound trajectory segments, respectively. If the mechanism responsible for the decametric radiation is greatly dependent upon the ambient plasma densities at Io, as most current viable ideas suggest [cf. Goldreich and Lynden-Bell, 1969; Gurnett, 1972; Shawhan et al., 1973] then these severe fluctuations of densities will undoubtedly have a profound effect upon decametric emissions. For example, if the large gradient of plasma densities faithfully follows magnetic shells around Jupiter and the magnetic field of the planet is well approximated by that of an offset tilted dipole, then large fluctuations of densities will be encountered by Io due to both the planetary rotation and the moon's slower orbital motion. Further, if the displacement of the dipole from the planet's center does not lie within the plane defined by the tilting of the dipole from Jupiter's rotational axis, then Io at fixed orbital phase will experience two density maxima of differing magnitudes and separated by approximately 180° of planetary rotation for each sidereal rotation period of Jupiter. It is of interest to note that if there are higher-order moments of the Jovian magnetic field, the plasmapause could feature further substantial variations in position relative to the orbit of Io. Structures in the density distributions in the Io flux tubes, which are caused by the passage of Io or by other phenomena, appear relatively long-lived in the initial assessment. For example, the gradient drift velocity of a 100-eV proton at the equator, $3cE(qBR)^{-1}$ in cgs units, is only about 7 kilometers per Jovian rotation period. The departure from a strictly corotating orbit due to drifts from cross-tail electric fields associated with solar wind flow past the Jovian magnetosphere is also probably of no primary significance. Clearly the relationship of the Jovian plasmapause and Io-modulation of the decametric radiation deserves further exploration.

Europa is embedded in the lesser proton densities of the ring current. Measurements within the ring current during inbound and outbound traversals indicate that this giant torus of plasma is approximately axially symmetric. Proton densities in the Europa flux tubes are 10 to 15 $(cm)^{-3}$, and there is no indication of a salient plasma feature such as found at Io. The more distant two moons Ganymede and Callisto will traverse the thin, tenuous plasma disc with plasma densities $\leqslant 1\ (cm)^{-3}$.

In lieu of any known sensible mechanism for transporting solar wind ions from the magnetopause to positions deep within the Jovian magnetosphere, which will account for the presence of the high densities <u>and</u> low energies in the plasmasphere and ring current, we conclude that the source of these protons is the Jovian ionosphere.

A cloud of atomic hydrogen was found at the orbit of Io via measurements with an ultraviolet photometer on Pioneer 10 [Carlson and Judge, 1974]. The geometry of this hydrogen cloud in orbit around Jupiter was that of a partial torus with azimuthal dimensions of about 120° in the equatorial plane. These hydrogen atoms are believed to have escaped from the moon Io and lack sufficient velocity to escape from bound orbits in the Jovian gravitational field [McDonough and Brice, 1973]. By estimating the hydrogen escape velocities tangent to the orbit of Io, Carlson and Judge were able to estimate the lifetime of these atoms, which was necessary to limit their spatial distribution to a partial torus. This lifetime was 2×10^5 seconds. From our measurements of the low-energy proton intensities at the orbit of Io, the lifetime of neutral hydrogen due to charge exchange, τ, can be calculated. The omnidirectional proton intensity J_o is about 10^9 $(cm^2\text{-sec})^{-1}$ and the cross-section for charge exchange, σ, at 100 eV is 3.5×10^{-15} cm^2 [Fite _et al_., 1960]. Hence $\tau = (\sigma J_o)^{-1} \sim 3 \times 10^5$ seconds in good agreement with the above estimate on different grounds, when the inaccuracies of both calculations are considered.

Our future analyses will be directed toward measurements of electron intensities throughout the Jovian magnetosphere, determinations of corotational velocities in the ring current and plasma disc, and detailed examination of plasmas near and within the flux tubes of Io. Pioneer 11 will not only yield a second series of such observations, but will also penetrate into the gravitationally dominated region of the Jovian magnetosphere.

Acknowledgments

We are indebted to E. J. Smith for providing the magnetometer measurements which allowed us to calculate the pitch angles for the plasma measurements reported here. We would also like to express our appreciation and gratitude to the Pioneer Project Office at Ames Research Center and TRW Systems, Redondo Beach, California, for the successful Pioneer-10 Jupiter flyby. The other experimenters participating in analyses of Pioneer-10 plasma observations are H. R. Collard, D. S. Intriligator and D. D. McKibbin. The plasma instrumentation was constructed by Time Zero Laboratories, Torrance, California, and operated flawlessly throughout the mission. This research was supported in part at the University of Iowa by the National Aeronautics and Space Administration under grant NGL-16-001-002 and by the Office of Naval Research under contract N00014-68-A-0196-0009.

References

Brice, N. M., Bulk Motion of the Magnetosphere, J. Geophys. Res., 72, 5193, 1967.

Brice, N. M., and G. A. Ioannidis, The Magnetospheres of Jupiter and Earth, Icarus, 13, 173, 1970.

Carlson, R. W., and D. L. Judge, Pioneer 10 Ultraviolet Photometer Observations at Jupiter Encounter, J. Geophys. Res., 79, 3623, 1974.

Carr, T. D., and S. Gulkis, The Magnetosphere of Jupiter, Ann. Rev. Astron. Astrophys., 7, 577, 1969.

Chappell, C. R., Recent Satellite Measurements of the Morphology and Dynamics of the Plasmasphere, Rev. Geophys. Space Phys., 10, 951, 1972.

Eviatar, A., and A. I. Ershkovich, Dynamic Phenomena at the Jovian Magnetopause, Un. of Tel-Aviv Res. Rep. ES-74-050, 1974.

Fillius, R. W., and C. E. McIlwain, Measurements of the Jovian Radiation Belts, J. Geophys. Res., 79, 3589, 1974.

Fite, W. L., R. F. Stebbings, D. G. Hummer and R. T. Brackmann, Ionization and Charge Transfer in Proton-Hydrogen Atomic Collisions, Phys. Rev., 119, 663, 1960.

Frank, L. A., On the Extraterrestrial Ring Current During Geomagnetic Storms, J. Geophys. Res., 72, 3753, 1967.

Frank, L. A., and K. L. Ackerson, Observations of Charged Particle Precipitation into the Auroral Zone, J. Geophys. Res., 76, 3612, 1971.

Goldreich, P., and D. Lynden-Bell, Io, a Jovian Unipolar Inductor, Astrophys. J., 156, 59, 1969.

Gurnett, D. A., Sheath Effects and Related Charged-Particle Acceleration by Jupiter's Satellite Io, Astrophys. J., 175, 525, 1972.

Kliore, A., D. L. Cain, G. Fjeldbo, B. L. Seidel and S. I. Rasool, Preliminary Results on the Atmospheres of Io and Jupiter From the Pioneer 10 S-Band Occultation Experiment, Science, 183, 323, 1974.

McDonough, T. R., and N. M. Brice, A Saturnian Gas Ring and the Recycling of Titan's Atmosphere, Icarus, 20, 136, 1973.

Piddington, J. H., Jupiter's Magnetosphere, Un. of Iowa Res. Rep. 67-63, 1967.

Shawhan, S. D., R. F. Hubbard, G. Joyce and D. A. Gurnett, Sheath Acceleration of Photoelectrons by Jupiter's Moon Io, Photon and Particle Interactions with Surfaces in Space, ed. by R. Grard, D. Reidel, Dordrecht, 405, 1973.

Shelley, E. G., R. G. Johnson and R. D. Sharp, Satellite Observations of Energetic Heavy Ions During a Geomagnetic Storm, J. Geophys. Res., 77, 6104, 1972.

Simpson, J. A., D. C. Hamilton, R. B. McKibben, A. Mogro-Campero, K. R. Pyle and A. J. Tuzzolino, The Protons and Electrons Trapped in the Jovian Dipole Magnetic Field Region and Their Interaction With Io, J. Geophys. Res., 79, 3522, 1974.

Smith, E. J., L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, C. P. Sonnet and A. M. A. Frandsen, The Planetary Magnetic Field and Magnetosphere of Jupiter: Pioneer 10, J. Geophys. Res., 79, 3501, 1974.

Trainor, J. H., F. B. McDonald, B. J. Teegarden, W. R. Webber and E. C. Roelof, Energetic Particles in the Jovian Magnetosphere, J. Geophys. Res., 79, 3600, 1974.

Van Allen, J. A., D. N. Baker, B. A. Randall and D. D. Sentman, The Magnetosphere of Jupiter as Observed with Pioneer 10: 1. Instrument and Principal Findings, J. Geophys. Res., 79, 3559, 1974.

Warwick, J. W., Radiophysics of Jupiter, _Space_ _Sci_. _Rev_., _6_, 841, 1967.

Wolfe, J. H., J. D. Mihalov, H. R. Collard, D. D. McKibbin, L. A. Frank and D. S. Intriligator, Pioneer 10 Observations of the Solar Wind Interaction With Jupiter, _J_. _Geophys_. _Res_., _79_, 3489, 1974.

Figure Captions

Figure 1. Projections of the trajectory of Pioneer 10 onto the ecliptic plane during Jupiter encounter. Also shown are the positions of the three Galilean moons Io, Europa and Ganymede for crossings of their corresponding L-shells during the inbound (closed circles) and outbound (open circles) segments of the trajectory. The projections of the five fans of acceptance which comprise the plasma instrument total field-of-view are shown at two positions along the orbit. The axis of this field-of-view is directed along the spacecraft spin axis, and hence toward earth, throughout the Jupiter encounter.

Figure 2. Color-coded spectrograms of the logarithm of the plasma analyzer responses after the background currents due to penetrating charged particles have been substracted. The measurements were gained on 4 December and cover periapsis (0315 E.R.T.) and the outbound trajectory segment deep within the Jovian magnetosphere. The

crossing of the flux tubes of Io occurs at about 0630 to 0730 E.R.T.

Figure 3. Comparison of the observed directional intensities of protons with the background responses of the electrostatic analyzer and with the energetic electron intensities with E > 9 MeV for the series of observations of the upper spectrogram in Figure 2.

Figure 4. The proton densities within the energy range 108 eV to 4.80 keV of the electrostatic analyzer corresponding to the observations of Figure 2. The magnetic shell parameter L in units of Jovian radii R_J ($1\ R_J = 71{,}370$ km) and pitch angle α of the measurement of directional intensities are given along the top border.

Figure 5. Proton densities in the energy range 108 eV to 4.80 keV near and within the Io flux tubes observed during the <u>inbound</u> segment of the Pioneer 10 trajectory (cf. Figure 4).

Figure 6. Directional, differential spectrum of proton intensities observed within the

Jovian plasmasphere at Jovicentric radial distance $R = 3.33\ R_J$.

Figure 7. Directional, differential spectrum of proton intensities observed at $R = 2.85\ R_J$ near periapsis.

Figure 8. Directional, differential spectrum of proton intensities observed within the Jovian ring current at $R = 10.3\ R_J$.

Figure 9. Summary of major plasma features deep within the Jovian magnetosphere as viewed in a magnetic meridional plane.

Figure 10. Directional, differential spectrum of proton intensities observed within the Jovian plasma disc at $R = 14.2\ R_J$.

Figure 11. Comparison of the omnidirectional electron intensities $E > 160$ keV as reported by Fillius and McIlwain [1974] with features of the low-energy proton densities corresponding to the series of measurements of Figure 2.

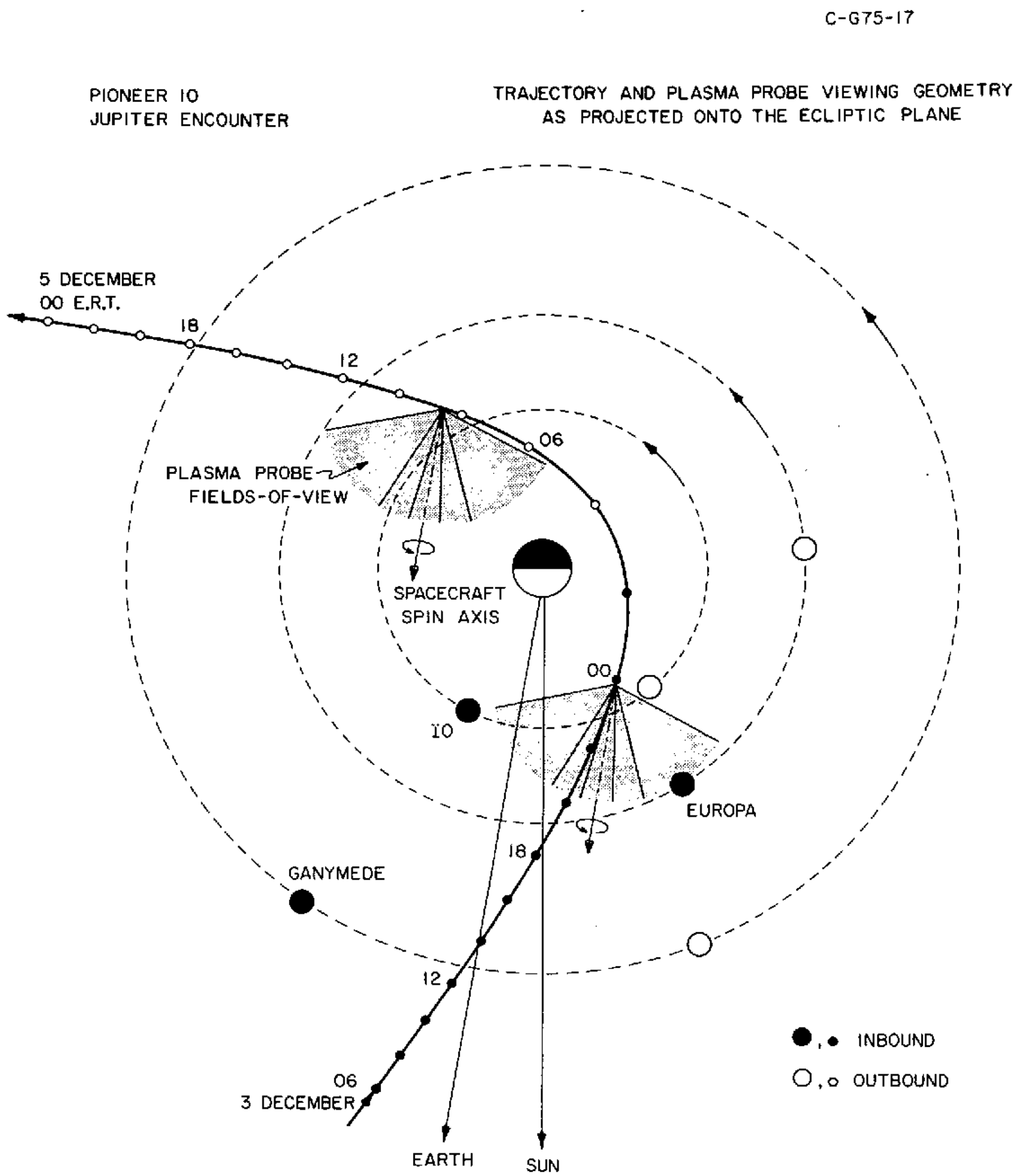
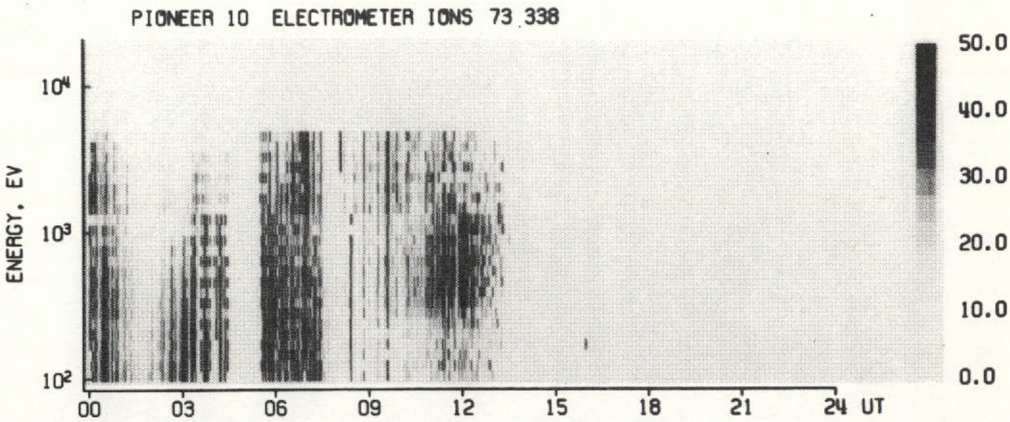

C-G75-17
PIONEER 10
JUPITER ENCOUNTER
TRAJECTORY AND PLASMA PROBE VIEWING GEOMETRY
AS PROJECTED ONTO THE ECLIPTIC PLANE
5 DECEMBER
00 E.R.T.
18
12
06
PLASMA PROBE
FIELDS-OF-VIEW
SPACECRAFT
SPIN AXIS
00
IO
EUROPA
18
GANYMEDE
12
06
3 DECEMBER
EARTH
SUN
INBOUND
OUTBOUND

Figure 1.



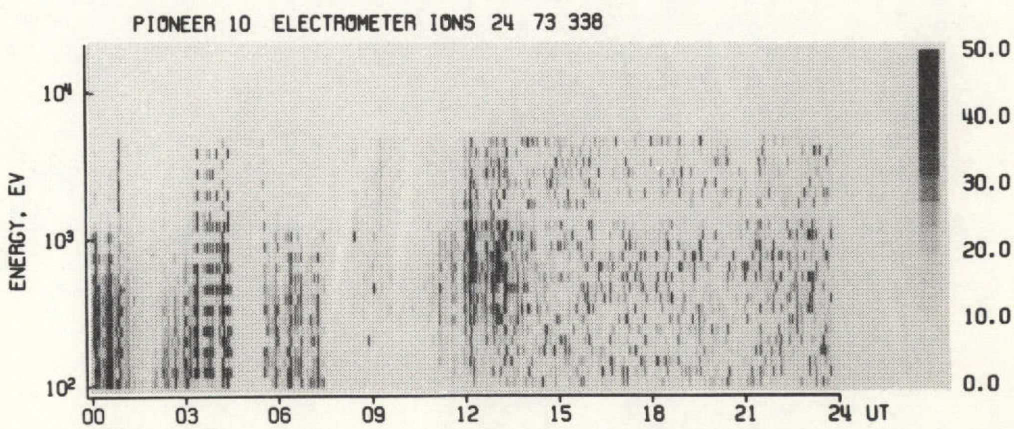
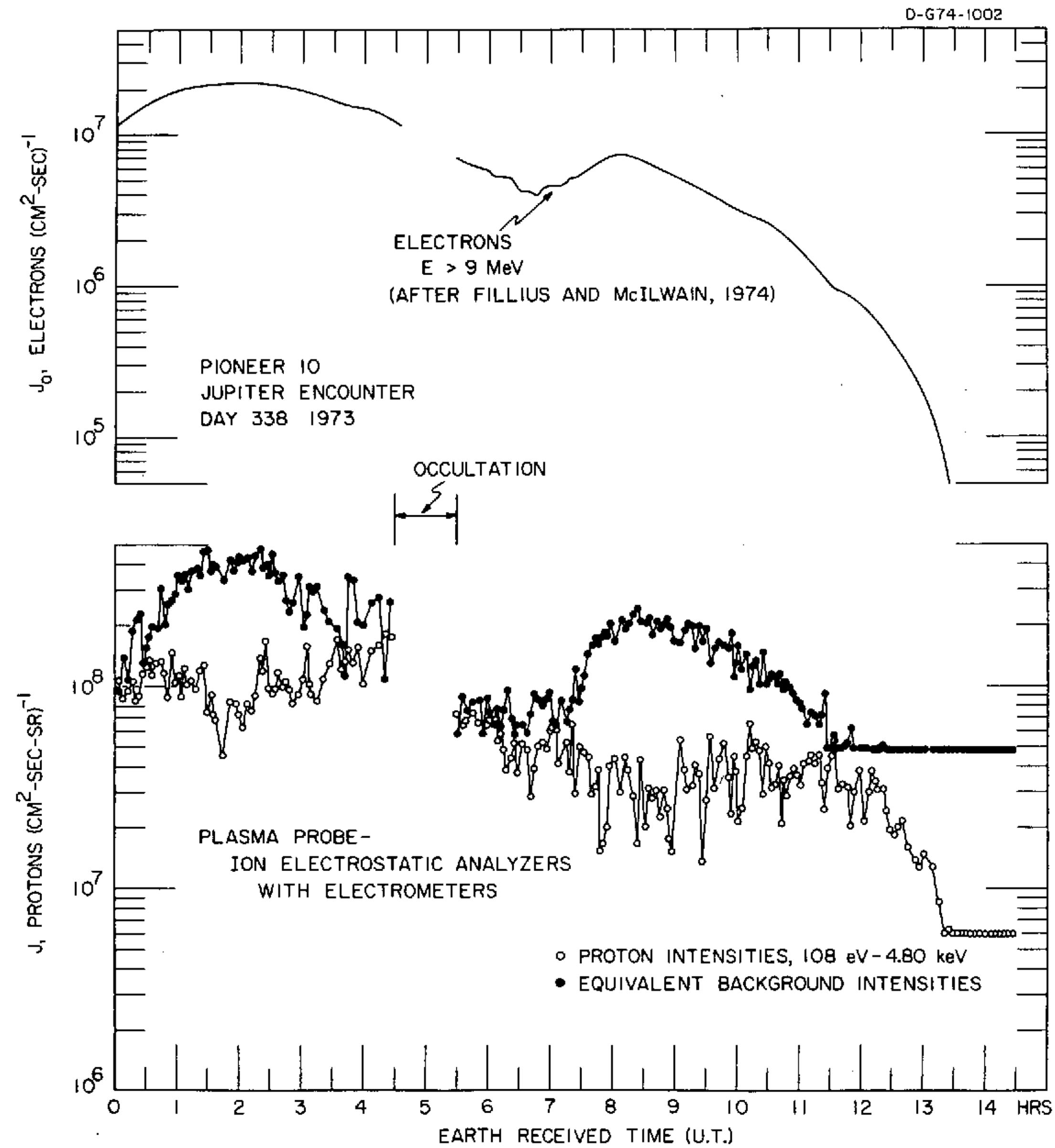


Figure 2.

ORIGINAL PAGE IS
OF POOR QUALITY



D-G74-1002
10^7
10^6
10^5
J_o, ELECTRONS $(CM^2\text{-}SEC)^{-1}$
ELECTRONS
E > 9 MeV
(AFTER FILLIUS AND McILWAIN, 1974)
PIONEER 10
JUPITER ENCOUNTER
DAY 338 1973
OCCULTATION
10^8
10^7
10^6
J, PROTONS $(CM^2\text{-}SEC\text{-}SR)^{-1}$
PLASMA PROBE-
ION ELECTROSTATIC ANALYZERS
WITH ELECTROMETERS
○ PROTON INTENSITIES, 108 eV - 4.80 keV
● EQUIVALENT BACKGROUND INTENSITIES
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 HRS
EARTH RECEIVED TIME (U.T.)

Figure 3.

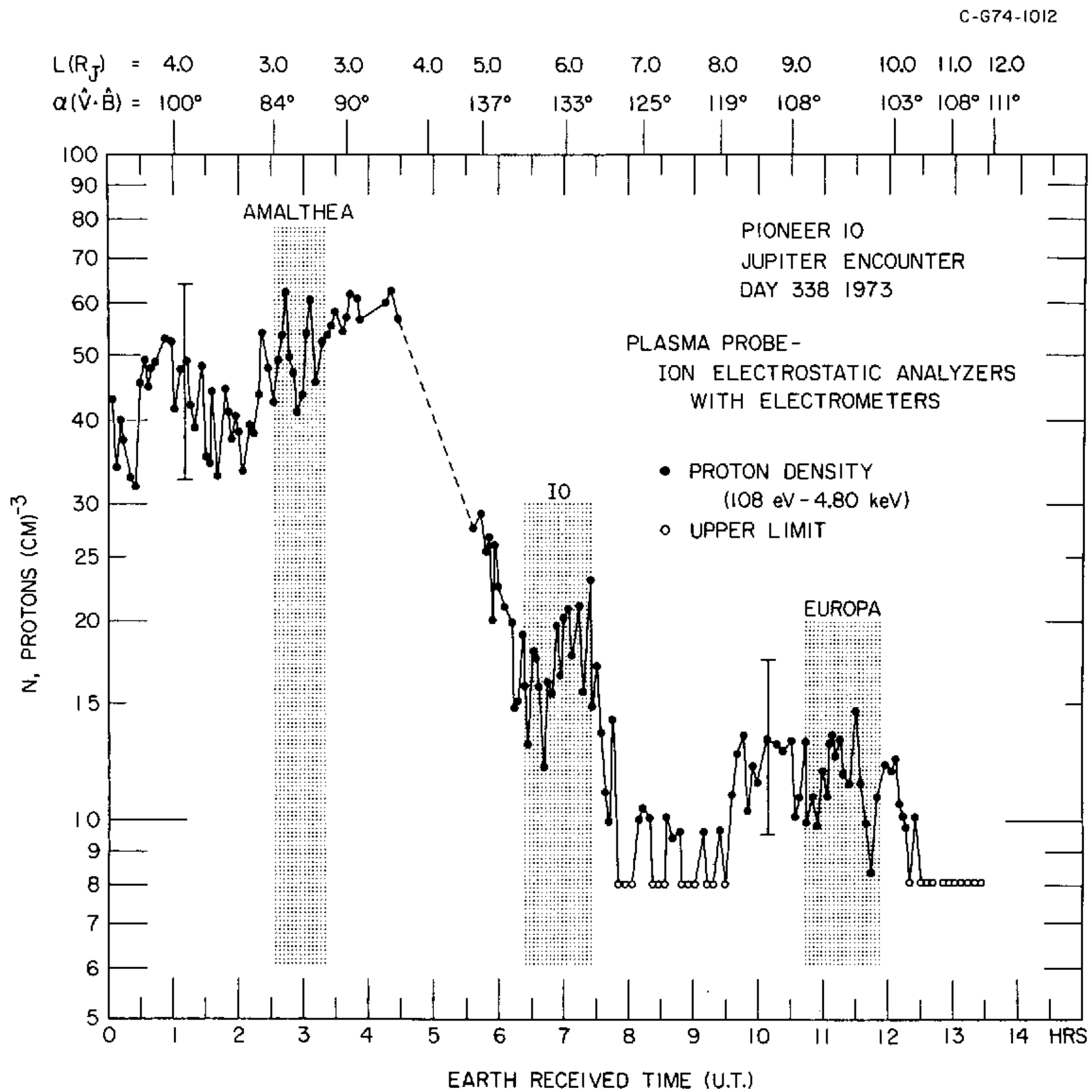

C-G74-1012
L(R_J) = 4.0 3.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0
α(V̂·B̂) = 100° 84° 90° 137° 133° 125° 119° 108° 103° 108° 111°
AMALTHEA
IO
EUROPA
PIONEER 10
JUPITER ENCOUNTER
DAY 338 1973
PLASMA PROBE-
ION ELECTROSTATIC ANALYZERS
WITH ELECTROMETERS
● PROTON DENSITY
(108 eV - 4.80 keV)
○ UPPER LIMIT
N, PROTONS (CM)^-3
EARTH RECEIVED TIME (U.T.)
HRS

Figure 4.

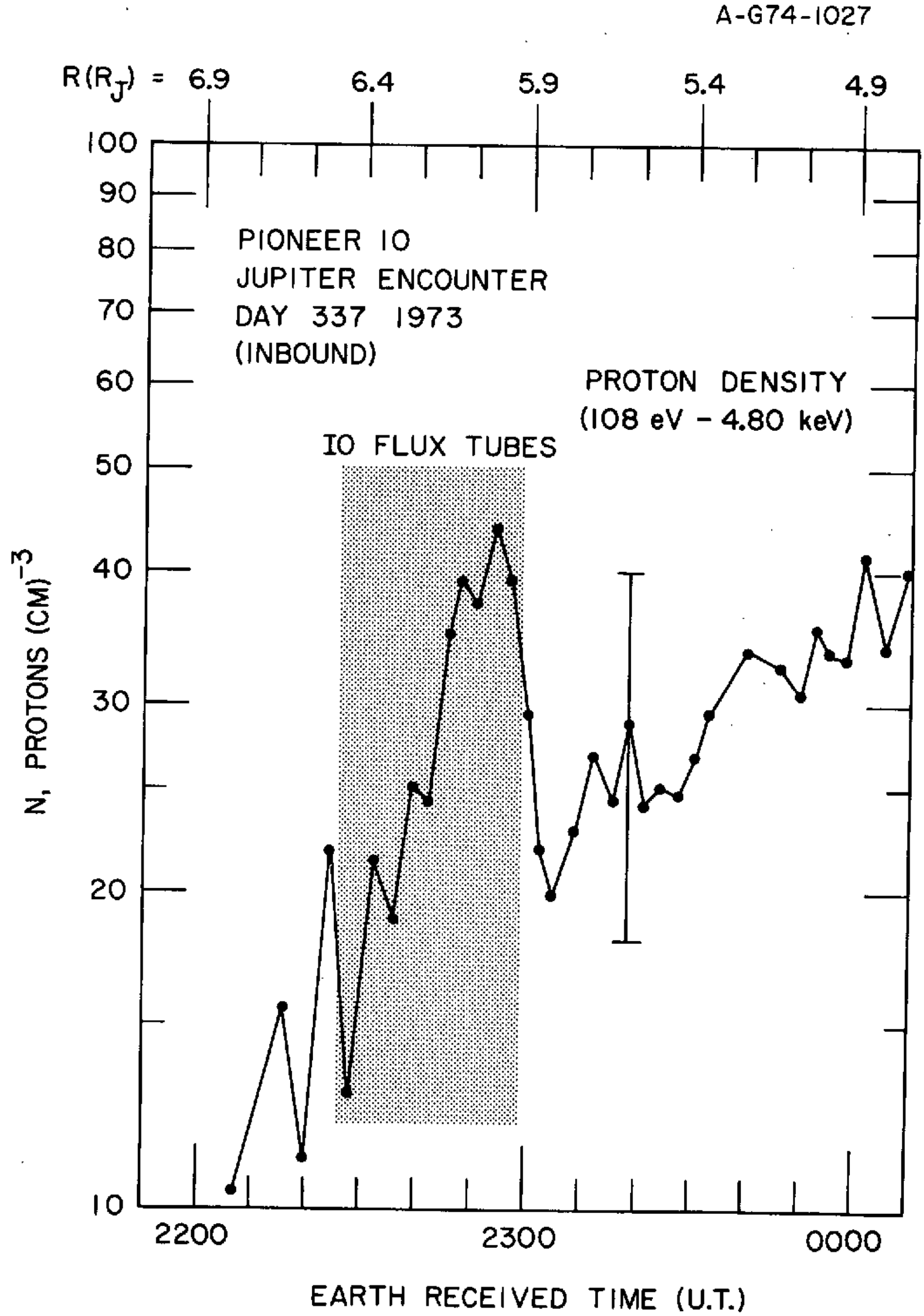

A-G74-1027
R(R_J) = 6.9
6.4
5.9
5.4
4.9
100
90
80
70
60
50
40
30
20
10
PIONEER 10
JUPITER ENCOUNTER
DAY 337 1973
(INBOUND)
PROTON DENSITY
(108 eV - 4.80 keV)
IO FLUX TUBES
N, PROTONS (CM)^-3
2200
2300
0000
EARTH RECEIVED TIME (U.T.)

Figure 5.

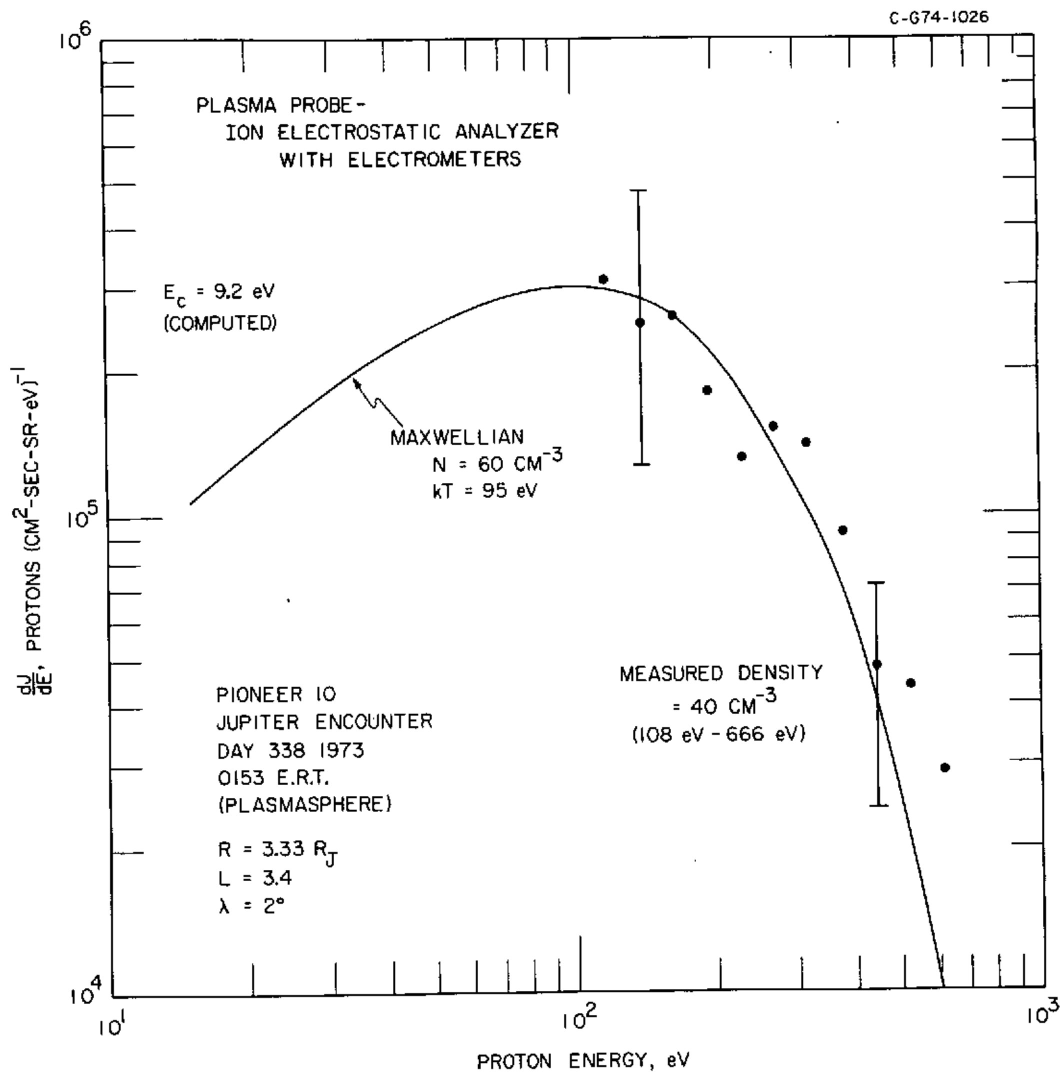

C-G74-1026
PLASMA PROBE-
ION ELECTROSTATIC ANALYZER
WITH ELECTROMETERS
E_c = 9.2 eV
(COMPUTED)
MAXWELLIAN
N = 60 CM^{-3}
kT = 95 eV
MEASURED DENSITY
= 40 CM^{-3}
(108 eV - 666 eV)
PIONEER 10
JUPITER ENCOUNTER
DAY 338 1973
0153 E.R.T.
(PLASMASPHERE)
R = 3.33 R_J
L = 3.4
λ = 2°
$\frac{dJ}{dE}$, PROTONS $(CM^2\text{-SEC-SR-eV})^{-1}$
10^4
10^5
10^6
10^1
10^2
10^3
PROTON ENERGY, eV

Figure 6.

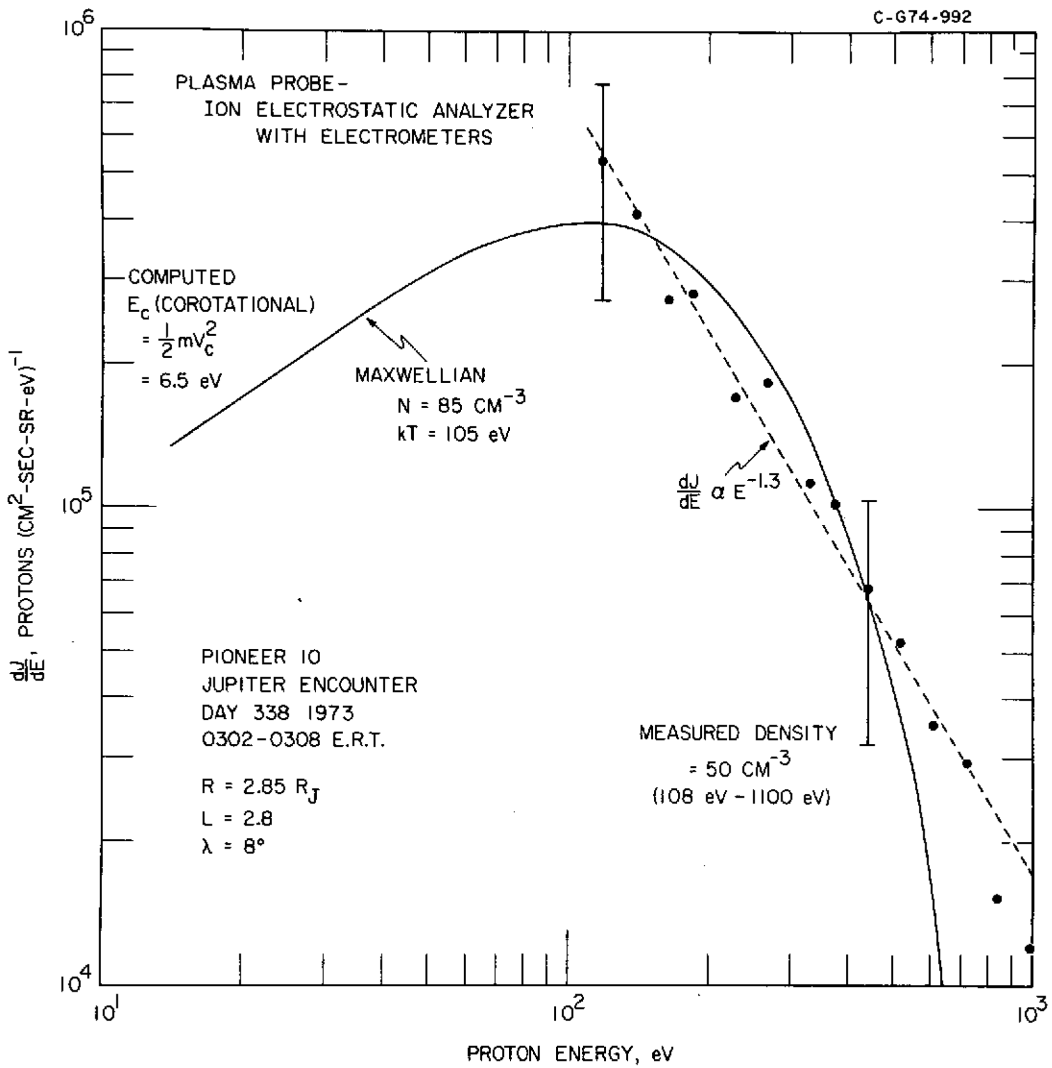

C-G74-992
PLASMA PROBE-
ION ELECTROSTATIC ANALYZER
WITH ELECTROMETERS
COMPUTED
E_c (COROTATIONAL)
$= \frac{1}{2} m V_c^2$
= 6.5 eV
MAXWELLIAN
N = 85 CM^{-3}
kT = 105 eV
$\frac{dJ}{dE}$ α $E^{-1.3}$
PIONEER 10
JUPITER ENCOUNTER
DAY 338 1973
0302-0308 E.R.T.
R = 2.85 R_J
L = 2.8
λ = 8°
MEASURED DENSITY
= 50 CM^{-3}
(108 eV - 1100 eV)
$\frac{dJ}{dE}$, PROTONS $(CM^2\text{-SEC-SR-eV})^{-1}$
PROTON ENERGY, eV
10^4
10^5
10^6
10^1
10^2
10^3

Figure 7.

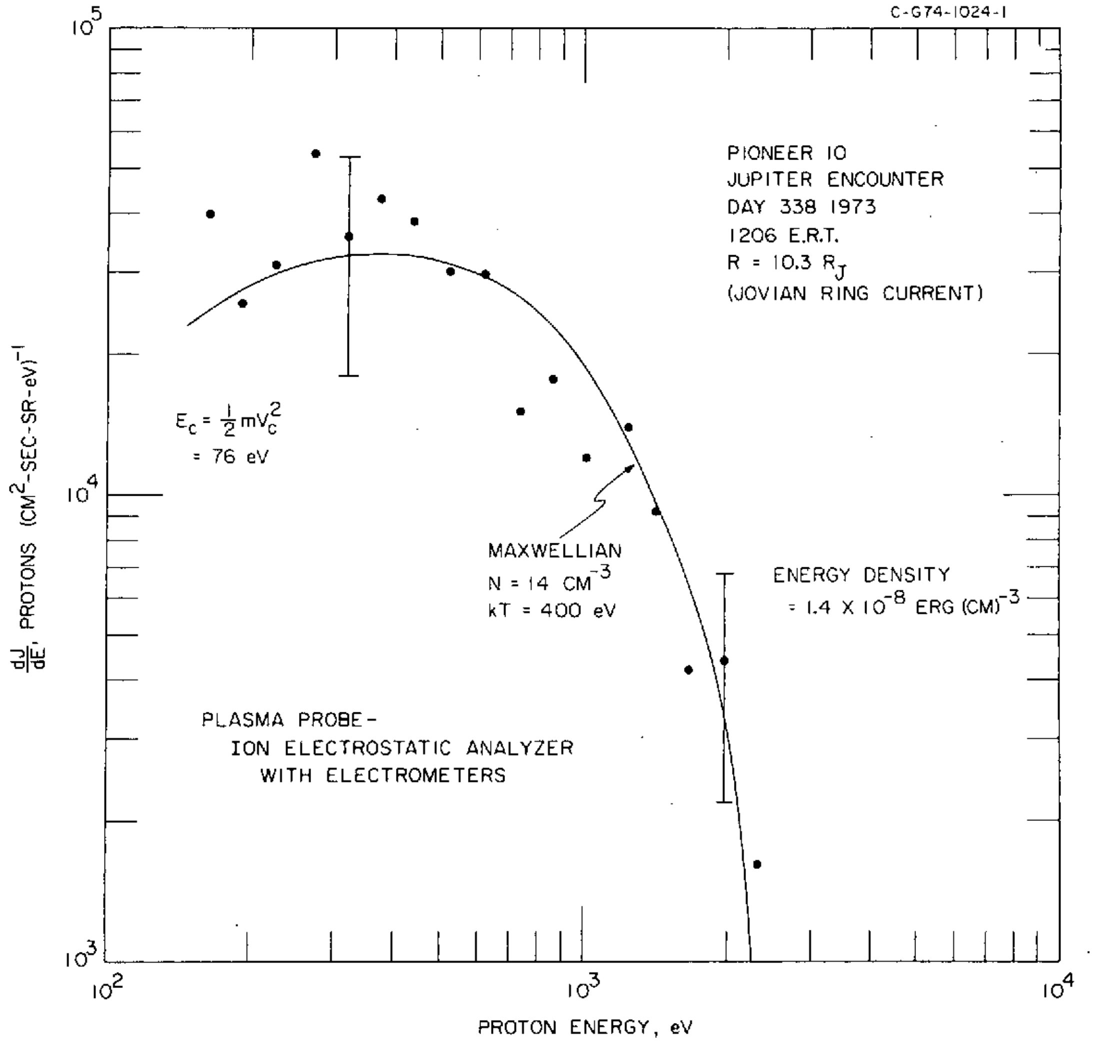
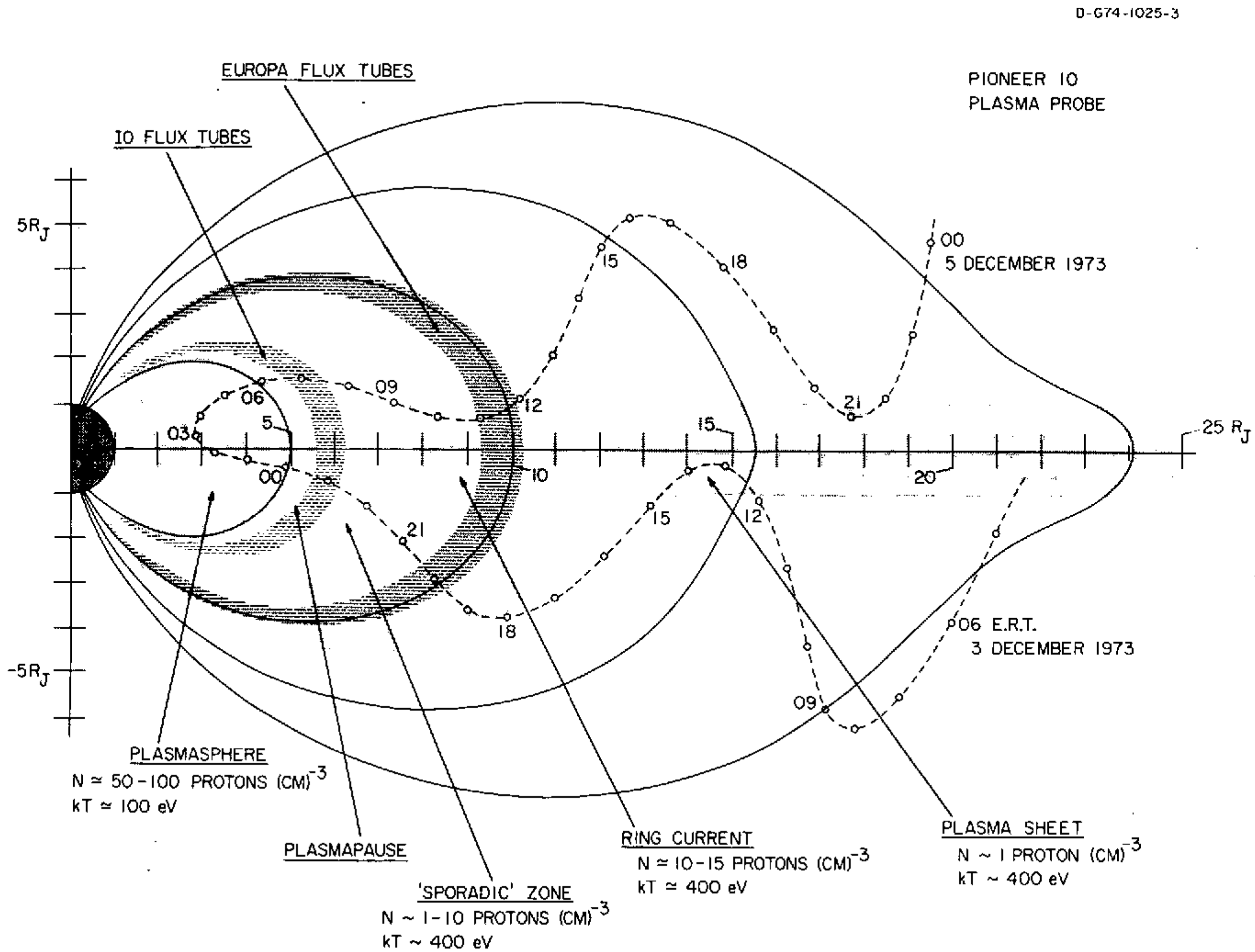

C-G74-1024-1
PIONEER 10
JUPITER ENCOUNTER
DAY 338 1973
1206 E.R.T.
R = 10.3 R_J
(JOVIAN RING CURRENT)
$E_c = \frac{1}{2} m v_c^2$
= 76 eV
MAXWELLIAN
N = 14 CM^{-3}
kT = 400 eV
ENERGY DENSITY
= 1.4 X 10^{-8} ERG $(CM)^{-3}$
PLASMA PROBE-
ION ELECTROSTATIC ANALYZER
WITH ELECTROMETERS
$\frac{dJ}{dE}$, PROTONS $(CM^2\text{-SEC-SR-eV})^{-1}$
10^5
10^4
10^3
10^2
10^3
10^4
PROTON ENERGY, eV

Figure 8.



PLASMAS WITHIN THE JOVIAN MAGNETOSPHERE

Figure 9.

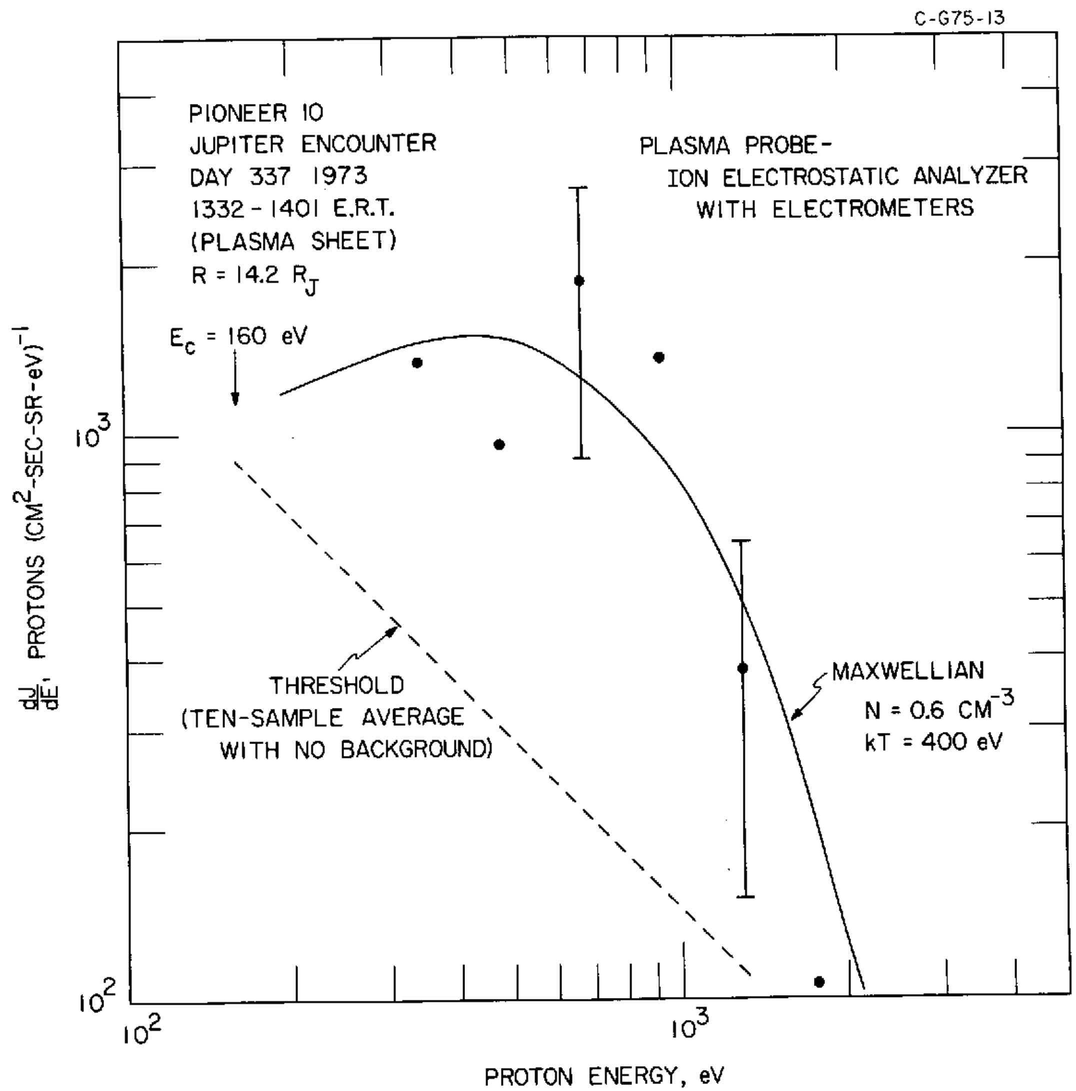

C-G75-13
PIONEER 10
JUPITER ENCOUNTER
DAY 337 1973
1332 - 1401 E.R.T.
(PLASMA SHEET)
R = 14.2 R_J
PLASMA PROBE-
ION ELECTROSTATIC ANALYZER
WITH ELECTROMETERS
E_c = 160 eV
THRESHOLD
(TEN-SAMPLE AVERAGE
WITH NO BACKGROUND)
MAXWELLIAN
N = 0.6 CM^{-3}
kT = 400 eV
$\frac{dJ}{dE}$, PROTONS $(CM^2\text{-SEC-SR-eV})^{-1}$
10^3
10^2
10^2
10^3
PROTON ENERGY, eV

Figure 10.

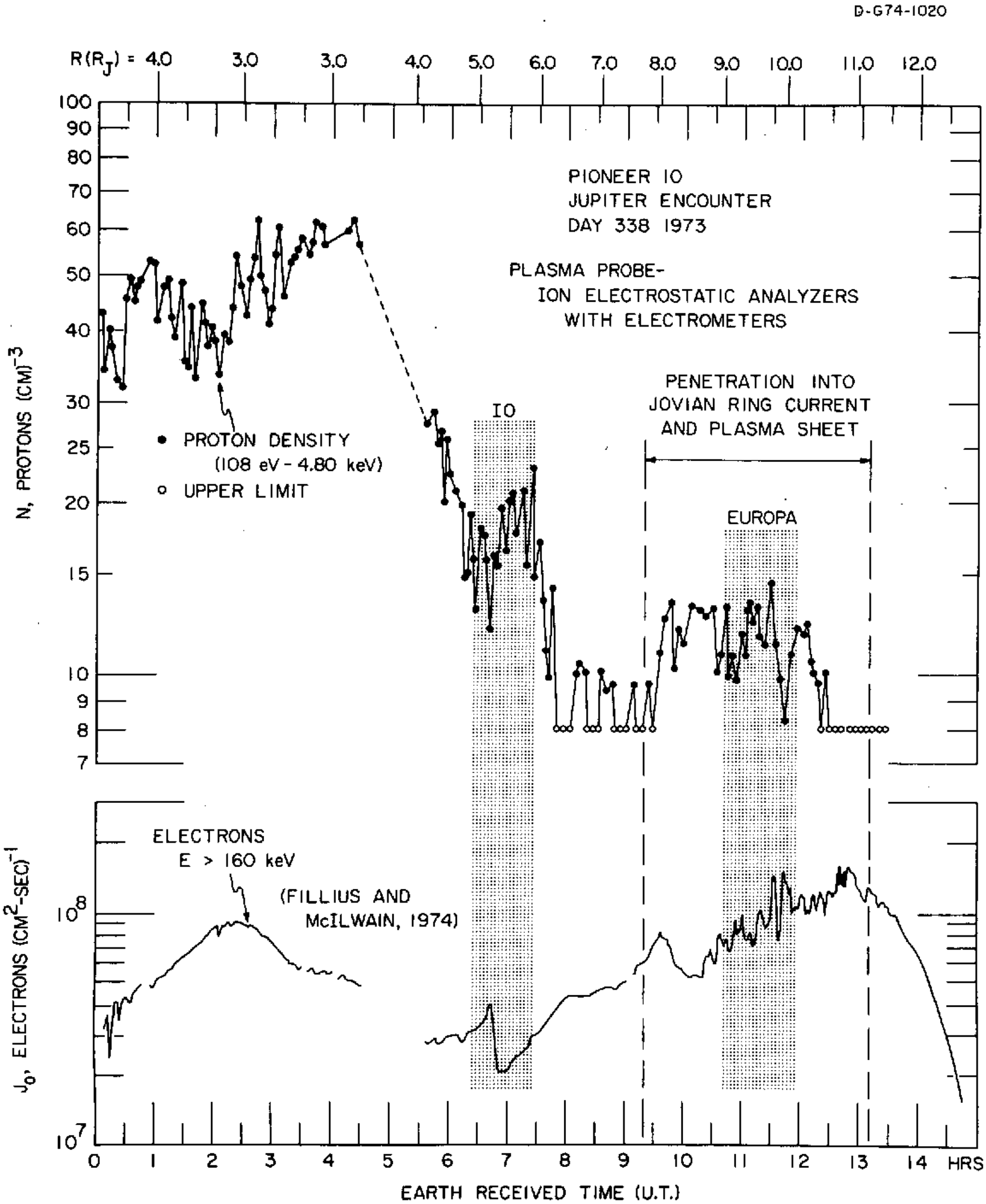

D-G74-1020
R(R_J) = 4.0 3.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0
PIONEER 10
JUPITER ENCOUNTER
DAY 338 1973
PLASMA PROBE-
ION ELECTROSTATIC ANALYZERS
WITH ELECTROMETERS
PENETRATION INTO
JOVIAN RING CURRENT
AND PLASMA SHEET
IO
EUROPA
PROTON DENSITY
(108 eV - 4.80 keV)
UPPER LIMIT
N, PROTONS (CM)$^{-3}$
ELECTRONS
E > 160 keV
(FILLIUS AND
McILWAIN, 1974)
J_0, ELECTRONS (CM^2-SEC)$^{-1}$
EARTH RECEIVED TIME (U.T.)
HRS

Figure 11.